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13. ABSTRACT

Lateral migration radiography (LMR) employs scattered photons to acquire detailed images of covered objects. Images of plastic encased real mines buried in soil using LMR have shown dramatic differences compared to images generated using simulated mines. The major characteristic that enables the discernibility of land mines to the degree of actual type identification is the presence of voids (air volumes) required for the operation of the fuse assembly or for blast direction control. Air volumes greatly modify the detected field of both one and multiple-scattered photons. The LMR system consists of an x-ray generator and two uncollimated detectors positioned to detect once scattered photons and two collimated detectors designed to detect primarily multiple-scattered photons. Air volumes modify both exit paths and the position of first-scatter events; they also modify the migration paths of multiple-scattered photons, thus producing different images in the two detector types. Monte Carlo calculations are performed with the MCNP code to obtain an understanding of the details of the photon lateral migration process. Images generated from these Monte Carlo calculations are in agreement with the experimental measurements. The real mine images confirm that LMR is capable not only of mine detection, but also of mine identification.

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Lateral migration radiography application to land mine detection, confirmation and classification

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Abstract. Lateral migration radiography (LMR) employs scattered photons to acquire detailed images of covered objects. Images of plastic encased real mines buried in soil using LMR have shown dramatic differences compared to images generated using simulated mines. The major characteristic that enables the discernibility of land mines to the degree of actual type identification is the presence of voids (air volumes) required for the operation of the fuse assembly or for blast direction control. Air volumes greatly modify the detected field of both once and multiple-scattered photons. The LMR system consists of an x-ray generator and two uncollimated detectors positioned to detect once-scattered photons and two collimated detectors designed to detect primarily multiple-scattered photons. The x-ray generator is located in the gap between symmetrically arranged detectors; the collimated x-ray beam typically has a spot size of 1.5×1.5 cm with perpendicular incidence on the soil surface. The optimal x-ray spectra for land mine detection with the LMR system range from 130 to 180 kVp with mean x-ray energies of from around 40 to 60 keV. Air volumes modify both exit paths and the position of first-scatter events; they also modify the migration paths of multiple-scattered photons, thus producing different images in the two detector types. The burial mode (below surface or laid on the surface) of the land mine can also be discerned by LMR due to a shadowing effect seen for surfaced-laid land mines. The presence of even a minute amount of metal in the land mine also aids in discerning the mine, because metal produces a signal decrease in both types of detectors. Monte Carlo calculations are performed with the MCNP code to obtain an understanding of the details of the photon lateral migration process. Images generated from these Monte Carlo calculations are in agreement with the experimental measurements. The real mine images confirm that LMR is capable not only of mine detection, but also of mine identification.
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1 Introduction

Lateral migration radiography (LMR) is a form of Compton backscatter imaging suggested by Campbell and Jacobs[1] of the University of Florida (UF). The UF land mine detection project developed a prototype LMR system and tested it in a laboratory setting for the detection of several simulated and real land mines. The LMR system consists of an x-ray generator and two sets of detectors along with a data acquisition system. As shown in Figure 1, the two uncollimated detectors are separated by a raster gap in the middle of which the x-ray incident beam is located. Adjacent to the uncollimated detectors, there are collimated detectors. Monte Carlo simulations of the LMR system show that the majority of once-scattered photons are registered by the two uncollimated detectors and the two collimated detectors mainly register the multiply scattered photons.

Recently, the project obtained temporary access to 12 real plastic land mines and acquired their Compton backscatter LMR images in the UF indoor land mine detection facility. The images of these real land mines showed dramatic differences compared to the images generated using simulated mines, while still maintaining the fundamental characteristics of LMR images. The air volumes in the mines appear prominently in the images and lead to unique signatures. This is a consequence of the unique combination of the external geometrical mine shape, low atomic number materials, e.g., plastic casing and explosive, and the particular internal geometrical shaped air volumes. Natural objects and other man-made objects rarely have this combination. Besides this feature, lateral migration shifting and shadowing effects exist in the collimated detector images. These latter features can be used to tell whether the land mine is on the surface or at a certain depth of burial. With these key signatures in the land mine LMR images, identification of land mine type by LMR image analysis is highly likely.

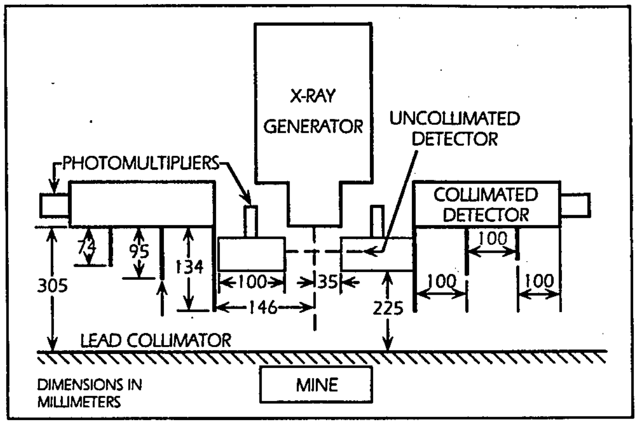

Fig. 1 Schematic of experiment setup used for the LMR land mine detection measurements.

2 System Configuration

The experimental setup for LMR land mine detection includes an x-ray generator, a pair of uncollimated detectors, a pair of collimated detectors, a computer controlled data acquisition system and a moveable soilbox driven by two computer controlled motors.

The x-ray generator used in the UF land mine detection system is a General Electric Maxitron 300, which has half-wave rectified output at 1,200 Hz. The images of the real land mines were acquired by using this x-ray generator at 150 kVp and 5 mA. The x-ray spectrum is a typical bremsstrahlung spectrum and the collimated x-ray beam provides an illumination of at least 2 million photons per 1.5×1.5 cm pixel. This Maxitron 300 was manufactured in 1950 and is very cumbersome. Because of the difficulty of moving this generator, a moveable soilbox was made to achieve the same effect of x-ray beam scanning. The direction along the gap between the two uncollimated detectors is called the raster direction and the direction orthogonal to this is called the motion direction. By using computer controlled motors to move the soilbox, the x-ray beam can scan the soilbox much the same as if the x-ray generator were on a moving vehicle. After defining the positive and negative direction of vehicle motion, the two pairs of detectors are identified as the front and rear uncollimated detectors and front and rear collimated detectors. The detector signals are sampled via an analog-to-digital (A/D) converter, sent to a computer, and stored as image data.

3 Principles

The LMR system design was optimized by using Monte Carlo simulations. During the simulations, various parameters of the system, e.g., raster gap width, collimator length, detector area, etc., were tested. The optimized system design is shown in Figure 1. With measurement output and the aid of the Monte Carlo simulation code, MCNP (Ref. 2), the physical principles of lateral migration Compton backscatter photon imaging are fairly well understood.[3]

As the x-ray beam scans the surface of the soil, the locations of the x-ray beam on the surface are used as the image pixel locations and the signals received by the four detectors are the pixel intensity values of each of their respective images. The detected field is digitized by these pixels. When the x-ray generator is set at 150 kVp and 5 mA, two kinds of interactions dominate the photons migration in the material: the photoelectric effect and Compton scatter. These two interactions are functions of photon energy, material effective atomic number and electron density. The photoelectric effect is dominant when photon energy is low, e.g., less than 20 keV, and material effective atomic number is high, e.g., higher than 26, while Compton scatter exists at various photon energies and is dominant in the materials with low effective atomic numbers. Because the detectors register the backscattered photons, whose intensity is decreased by the photoelectric effect, materials with different effective atomic numbers show differences in the acquired LMR images. The effective atomic number of a plastic mine is about 6 or 7 and that of the soil is at about 10 or 11. In our case, since the soil (sand) is mainly composed of the element silicon, the effective atomic number is greater than 10. In the acquired images (Figures 2–6), the signal intensity difference between plastic mines and soil shows up clearly. The higher intensity areas in the images correspond to the plastic case and explosive of the mine and the relatively lower intensity areas are the response of the soil. For metal encased mines, the effect is different. The photoelectric effect dominates the interactions. The effective atomic number of metal is greater than that of the soil, so the photoelectric effect in metal is greater than in soil. Photons are absorbed in metal more than in soil and in the images from the uncollimated and collimated detectors, the low intensity areas correspond to the metallic mine while the high intensity areas are the response of the soil.

Monte Carlo simulations and experiments demonstrated the different ways in which the uncollimated and the collimated detectors function in an LMR system. The uncollimated detectors mainly register once-scattered photons, which carry information on surface features. In contrast, the collimated detector images show both surface features and buried features by registering the multiply scattered photons. Photon lateral migration is very prominent in the collimated detector images. In the collimated images of Figure 2, motion direction shifting exists in both the front and rear detector images and their shifting directions are opposite. For a plastic mine, since the Compton scatter cross section is greater than that of the soil, the number of multiply scattered photons emitted from the mine is greater than that from the soil and this causes the intensity difference in the images. Among the multiply scattered photons, the ones migrating through mine have a higher probability of being scattered out of the soil and registered by detectors. Therefore, when the x-ray beam is scanning toward the mine, the forward direction migrating photons are emitted more than those of any other direction and are registered predominately by the front collimated detector. Similarly, when x-ray scanning away from the mine, the rear detector registers more Compton scatter photons than the front detector. Due to these behaviors, the highest intensity in the front collimated detector image tends to show up earlier than the physical center of the mine, which appears as backward shifting. In the rear collimated detector image, the opposite happens. This shifting is proportional to the depth of burial of the land mine; therefore, the depth of burial of the mine can be estimated from the amount of shifting.

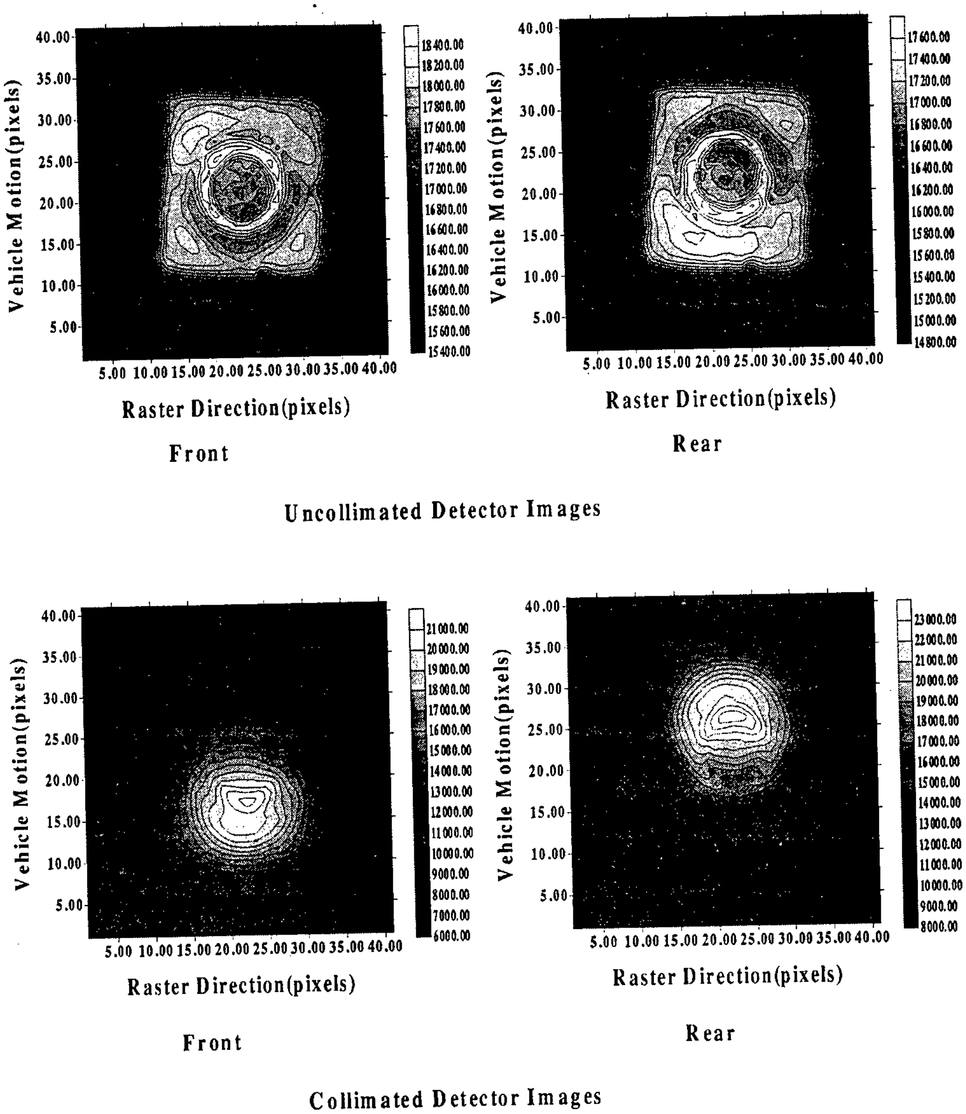

Fig. 2 LMR images of live M-19 mine; 2.54 cm depth of burial, 1.5 cm resolution.

4 Features of LMR Images

Air volumes are key identifying features in LMR images, especially when combined with the geometric shapes of the land mines. Even though air has a relatively high effective atomic number, the density is extremely small compared to that of soil, plastic and explosives. Basically, air gives free flight to the photons. To operate the fuse assembly, air volumes are essential to almost any land mine. The existence of air volumes dramatically modifies the once-scattered photon exit path as well as the multiply scattered photon migration path, compared to the simulated mines that lack these air spaces. When the x-ray beam is directly scanning over the air volumes, the photons that can pass through the surface material without any interaction will interact with the bottom or side wall of the fuse well. The solid angles subtended by the LMR detectors for these photons are smaller than those for the photons interacting with a simulated mine without air volume. For all the photons at the first-collision sites, the probability of not being registered by the uncollimated detectors is higher than that of the simulated mine case. As a consequence, an intensity decrease occurs at the location of the center of the air volume in the uncollimated detector images (Figure 3). When the x-ray beam is scanning right at the edge of the air volumes, photons emitted in the direction of the air volume have a higher probability of being registered by the uncollimated detectors than the photons emitted in the direction of the mine material. Therefore, there are high intensity areas right at the edge of the air volume and they occur at the front and back edge of the air volume in the rear and front uncollimated detector images, respectively (Figure 4). For multiply scattered photons, the existence of the air volume modifies the photon field in the transport media. The air volume essentially gives free flight to the migrating photons but the multiply scattering of photons tends to average out the effect and there is not as much evidence of the air volume in the collimated detector images. Therefore, in Figures 2 and 4, the collimated detector images show a more diffused air volume. A tiny amount of metal in the fuse emphasizes the intensity decrease in mid air volume as in Figure 3.

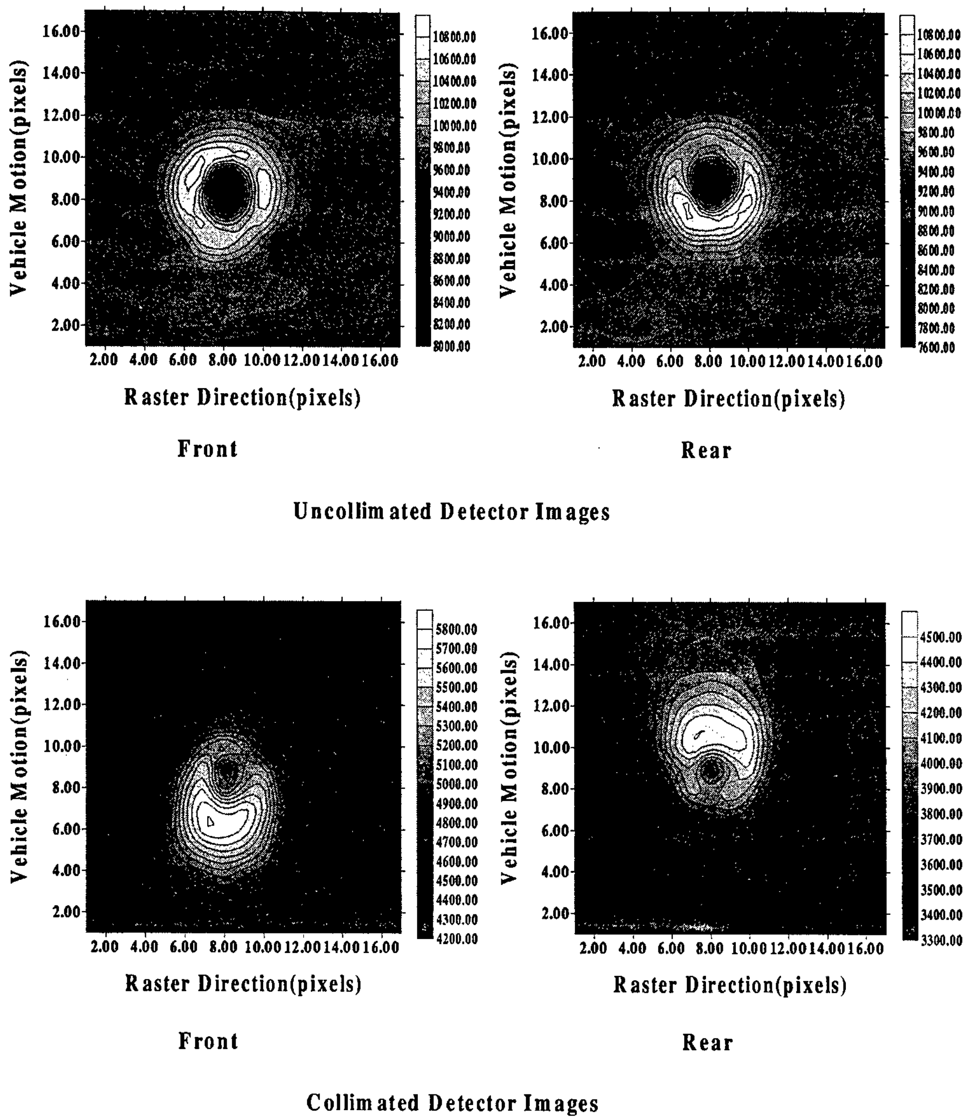

Fig. 3 LMR images of live TS/50 mine; flush buried, 1.5 cm resolution.

There are shadowing effects in the LMR images if the land mines are laid on the soil surface. In Figure 5, the shadows clearly accompany the mine images of both the collimated and uncollimated detectors. The shadows are roughly symmetric about the raster direction axis when we compare the two uncollimated images or two collimated images. In contrast, there is no shadowing effect in the images of Figure 3. Shadowing effects are the result of the surface laid mine physically blocking some of the Compton scatter photons. As the x-ray beam scans toward the mine, some of the Compton scatter photons emitted from the soil cannot reach the front detectors because of blocking by the land mine. Similarly, as the x-ray beam moves away from the mine, some of the Compton photons are blocked so they cannot be registered by the rear detectors. Therefore, the shadows are behind the mine in the front detector images and in front of the mine in the rear detector images. In the real world, antipersonnel mines are usually put either on the soil surface or they have a shallow depth of burial, normally not more than a few centimeters. The surface laid land mines can be easily recognized by both the shadowing effects and the vivid air volumes signature in combination with the mine geometric shape in LMR images.

By analyzing the 12 live mine LMR images,[4] we found the ratio of maximum intensity value to minimum intensity value shows some identifying characteristics of the mines. The ratio for the uncollimated detector images is always smaller than that of the collimated detectors images. The reason is that the material electron density difference is greatly emphasized by multiply scattered photons, which are primarily registered by the collimated detectors. The data for these 12 mines are shown in Table 1. For the uncollimated detector images, these ratios are roughly in the range of 1 to 2, while the ratios for collimated detector images are usually above 2. In future image processing and analysis, correlation of uncollimated and collimated detector image intensity ratios for potential mine objects will provide auxiliary information in LMR land mine detection.

Another feature of LMR images is that there is a similar response in uncollimated and collimated detector images for both plastic mines and metallic mines. In an LMR image, plastic mines cause intensity increase in both uncolli-

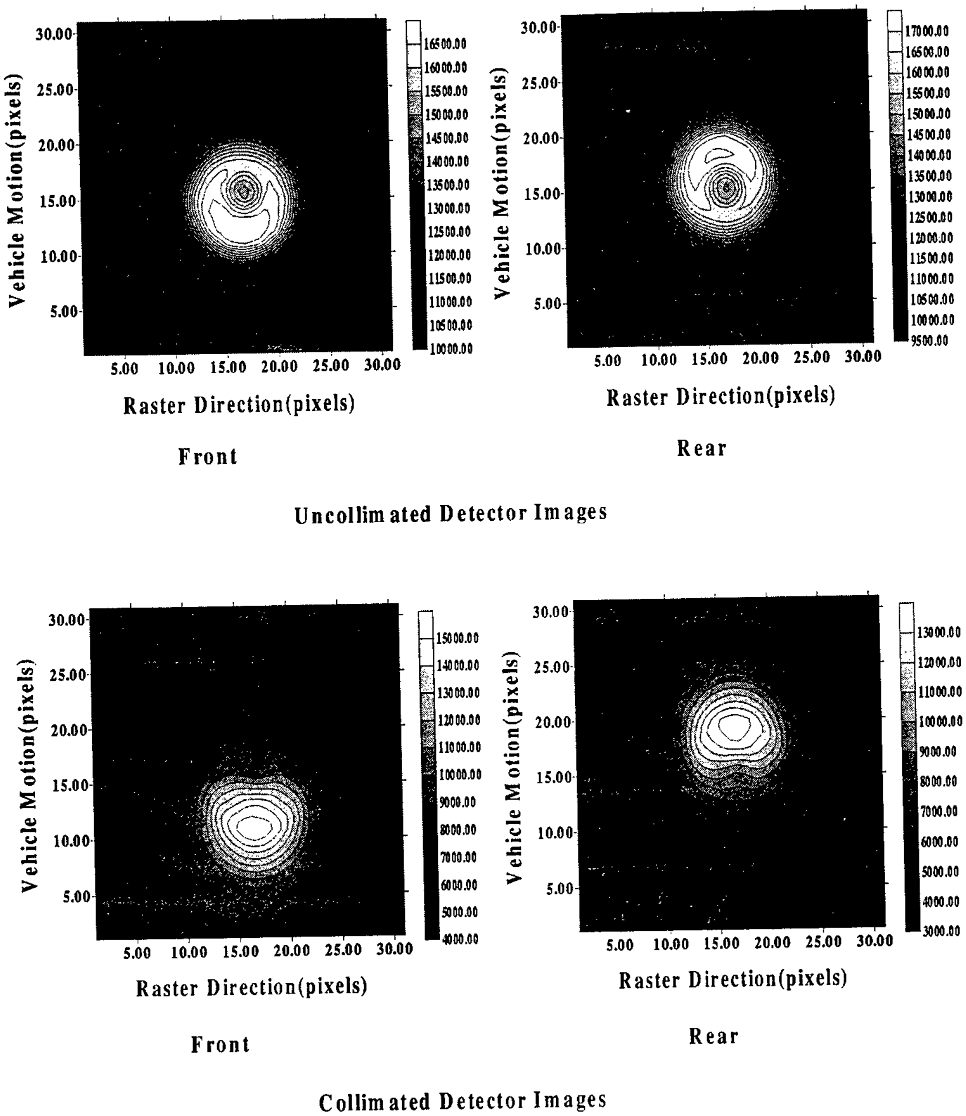

Fig. 4 LMR images of live VS-1.6 mine; 2.54 cm depth of burial, 1.5 cm resolution.

mated and collimated detectors and metallic mines cause decreases in both kinds of detectors. Other objects, such as potholes,[5] cause an increase in collimated detector images and a decrease in uncollimated detector images. Image correlation analysis will help eliminate some nonmine objects. Detailed information can be obtained in a paper by Wehlburg.[6]

With all these features of LMR images, not only can land mine detection be accomplished, but also mine type identification or at least mine type classification becomes possible. In Figure 6, the three peaks in the images are located at the plastic caps covering three fuse wells. These peaks are caused by air volume as well as plastic cap presence. These three peaks on a circular disk image are unique compared to the images of other land mines and identification of this as a TMA-4 antitank mine is highly probable. The M19 images in Figure 2 provide another example of a unique signature that results from the fuse well void spaces in the mine and the mine geometric shape. Type identification for the TS/50 and VS-1.6 through the acquired images (Figures 3–5) is more difficult because of their common feature of circular shapes with air volumes in the center of the mines, but recognizing and classifying them as a class of circular mines with center air volumes is fairly positive with this unique feature to land mines. Also, from the size of the circular mines in the images, the mine in Figures 3 and 5 is clearly an antipersonnel mine, while the mine in Figure 4 is clearly an antitank mine.

5 Conclusions

In a laboratory environment, LMR was theoretically and experimentally shown to be capable of land mine detection by the UF land mine detection research group. Currently, the group is developing a mobile LMR land mine detection module working for field testing. The LMR system can detect both surface objects and buried objects down to a depth of 10 cm. The uncollimated detectors primarily register surface features and the collimated detectors detect both surface features and subsurface features that originate from structured electron density discontinuity. Live land mine LMR images show that air volumes yield definitive

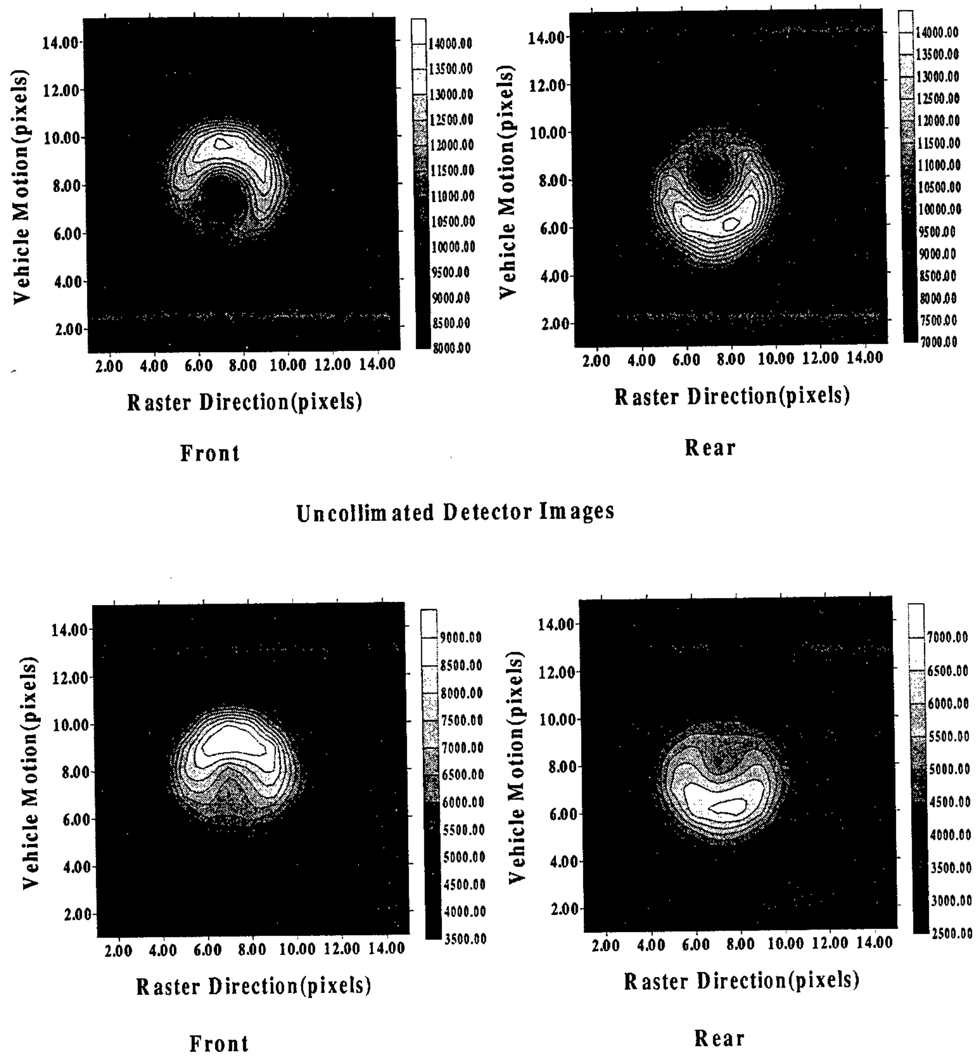

Fig. 5 LMR images of live TS/50 mine; on surface, 1.5 cm resolution.

Table 1 The ratio of maximum to minimum intensity of uncollimated detector and collimated detector response for 12 live mines.

Mine	Type	Dimensions (cm)	Uncollimated Detector Response Ratio		Collimated Detector Response Ratio		Depth of burial (cm)
			Front	Rear	Front	Rear	
M19	AT	33.3×33.3	1.20	1.19	3.80	3.50	2.5
PTMI-BA3	AT	D=32.8	1.30	1.30	5.00	4.67	2.5
TM-62P2	AT	D=30.7	1.33	1.34	2.33	2.36	2.5
VS-MK2	AP	D=8.9	1.58	1.56	2.00	2.11	Surface
TM-62P3	AT	D=30.7	1.94	1.76	1.56	1.64	2.5
VS-50	AP	D=8.9	2.05	2.16	2.44	2.44	Surface
TMA-4	AT	D=28.4	1.24	1.26	1.79	1.77	2.5
TS/50	AP	D=8.9	1.60	1.79	3.43	3.00	Surface
TYPE 72	AT	D=26.9	1.09	1.09	2.60	2.27	2.5
VS-2.2	AT	D=24.1	1.07	1.06	2.40	2.09	2.5
TMA-5	AT	31×27.4	1.22	1.20	5.50	5.25	2.5
VS-1.6	AT	D=22.1	1.64	1.72	4.01	4.23	2.5

AT, antitank; AP, Antipersonnel.

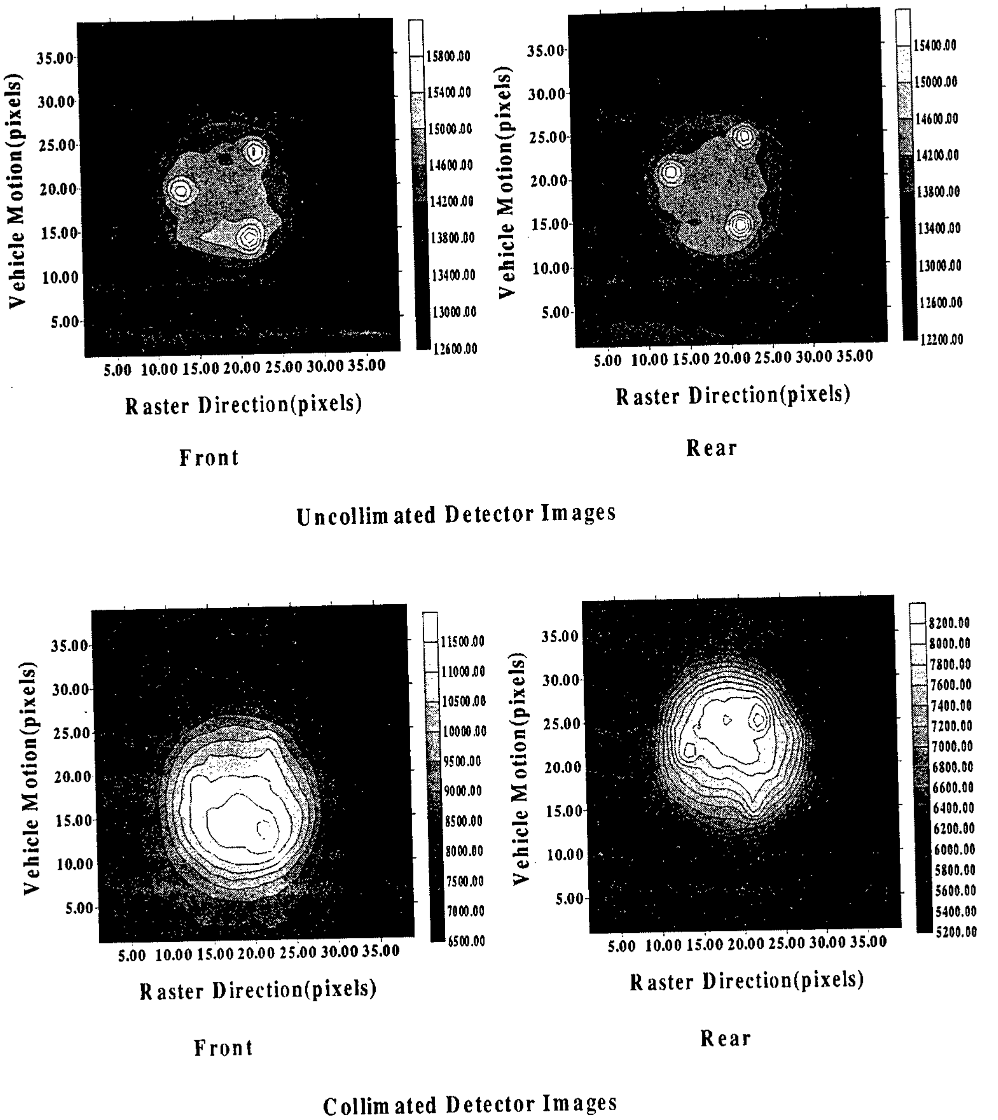

Fig. 6 LMR images of live TMA-4 mine; 2.54 cm depth of burial, 1.5 cm resolution.

signatures for mines and from the combination of these signatures and the mine's geometric shape in the image, identification of land mine types is highly probable. Shadowing effects and motion direction shifting of the mine in the collimated detector images provide information on depth of burial of the mine. Uncollimated detector and collimated detector image correlation analysis can help us identify nonmine objects.

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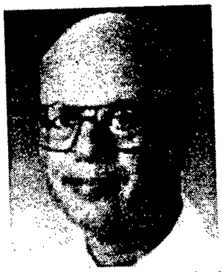

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